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PRINCIPAL INVESTIGATOR:	Benjamin M. Siegel

INTERACTION OF HIGH RESOLUTION FIELD ION PROBES WITH MATERIALS

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Benjamin M. Siegel

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SUMMARY

Ion beam lithography (IBL) can be expected to have significant advantages over electron beam lithography (EBL). The ions deposit much more energy per charged particle and thus resists are typically 50-100 times more sensitive to ions than to electrons. Also the range of the ions is well defined by their incident energy and there is no backscattering that causes the proximity effects which are a serious limitation in electron beam lithography. This means that very high resolution configurations could be structured by direct write ion beam lithography using single resist layers on thick substrates. It is our task to develop the instrumentation required to produce high resolution, high current density probes that could be used to investigate the interactions of ions with resists and substrate materials, evaluate the potential and feasibility of ion beam lithograhy and produce structures and devices with dimensions in the range of 10 to 100 nm.

We have concentrated our efforts on developing the ion beam lithography capability so we could investigate these potentials for structuring by direct writing with high resolution ion probes. Our approach and the instrumental developments that we have made are based on the use of the $H_2{}^+$ gaseous field ion source that we have developed ~~here at Cornell~~. This source represents an important breakthrough in providing a very high brightness ion beam of low mass ions, $H_2{}^+$, with high angular current density and low energy spread. Measured angular current densities ~~of 10~~ to 20μamp/sr are obtained routinely. The ion optical systems we have designed should be able to focus this beam to probes of 100-300 Å diameter with current densities greater than 100 amp/cm^2. The effective brightness of this probe is thus the order of 1×10^8 amp/cm^2/sr at 50 keV.

In the development of the instrumentation for investigating the characteristics and potential of ion beam lithography, we have first built a relatively simple experimental probe system designated as the Field Ion Probe System I, FIPS I. The optical system for the FIPS I was developed using a computer aided design (CAD) program that provides a rapid, interactive method for trying many configurations to determine the one that gives the desired optical characteristics. This method simulates the focussing and deflection properties of systems consisting of equi-diameter cylindrical electrodes and octupole deflectors. Using this method a five element lens with double octupole deflectors has been designed, giving calculated probe diameters of 102 Å deflected over a 0.2x0.2 mm field (2×10^4 beam diameters) without dynamic correction. These characteristics are obtained assuming operation under the following conditions: an acceptance half-angle of 2 mr, 30 keV beam energy and an energy spread of 1 eV. Taking the angular current

$dI/d\Omega$ = 10μa/sr and 20μa/sr, the current density in this 102 Å diameter probe would be 150 and 300 amp/cm^2 respectively. This ion optical system has been incorporated in a chamber that attaches to the existing H_2^+ field ion source. The chamber has a stage with x,y,z motion and a UHV specimen exchange lock. A schematic of this system is shown in Fig. 1.

This system will be used for making the initial studies on H_2^+ ion-resist interactions. A systematic investigation will be made of the sensitivities of various resists to the ion beam, development characteristics and resolution limits. With the very high current densities expected in the probes, very short exposure times will be required. Electronics have been built that will provide for rapid scanning with the double octupole deflectors.

A much more advanced field ion probe system has also been under development. This system was designed to provide real ion beam lithography capability for structuring high resolution devices. This summer (1982) we received a major gift from Hewlett-Packard that has greatly enhanced the level at which we will be able to carry out the instrumentation and the capability of the system for IBL. H-P has given Cornell the "HERMES," one of their prototype high speed, precision electron beam lithography systems explicitly to our project for our workon ion beam lithography. We will convert this instrument to an ion beam lithography system by replacing the field emission source and electron optical column with the field ion source and ion optical system that we have designed and developed. With the acquisition of this instrument we can develop a very advanced ion beam lithography capability utilizing the major part of the electronics, high accuracy interferometer controlled stage, UHV vacuum system and mechanical structure. The architecture of the H-P system is shown in the block schematic in Fig. 6. The subsystem components and their functions and how we can use or modify them for our applications are discussed in some detail in this report.

We have the basic designs for the ion beam column that is to replace the electron beam column of the HERMES. A design based on scaling up the new source developed for the FIPS I has been developed. Its construction waits on possible modification that may be desired after the results of the current investigations on ion beam sources now underway in NRRFSS are available.

We have designed a flexible, high performance ion optical lens system for this IBL system (HERMES II). This ion optical system has been designed to produce focussed probes ranging from 10 to 100 nm with high current densities that can be accelerated to energies ranging from 20 to 60 keV. The system has two lenses, the first lens focusses the beam to a cross-over at ground potential so that it can be blanked

rapidly with small deflection voltages close to ground potential. The second lens focusses this cross-over at the blanking aperture onto the substrate. The CAD programs developed for use in the design of this system are based on the charge density method for calculating the axial potential. Both lenses have four elements to make it possible to operate them in a "zoom" mode, i.e., fixed positions of the object (virtual source), the cross-over and the final probe image while the field ionization voltage (first electrode) and final accelerating potential can be varied. These conditions can be realized if there are two electrodes that can be freely varied in both the first lens that focusses the source to the cross-over at the blanking aperture and in the projector lens which operates as an "einzel" lens (same potential in its object and image space).

For the first lens we have found a physically and electrically asymmetric four element lens configuration that has superior optical characteristics to any three electrode lens we have investigated or has been reported to our knowledge. The performance characteristics of an ion optical system depend critically on the aberrations in the first lens for it is this lens that determines the size of the acceptance angle that can be used and hence the beam current that will be realized in the final high resolution probe. The projector lens that we have designed also gives superior performance by using a fourth electrode. The first and fourth electrodes of the einzel lens projector are set at the final accelerating potential which is the ground potential so the specimen stage and blanking aperture are also at or near ground potential. There are then two electrodes whose voltages can be varied to obtain good imaging over a range of accelerating voltages and different working distances. A post lens octupole deflector scans the probe over 10^4 beam diameters.

A column is being designed that will house the source and the ion optics and set in the same port of the work chamber that now takes the electron beam column of HERMES.

INTRODUCTION

The development of high brightness ion sources has opened up the possibility of using finely focussed ion beams for direct write ion beam lithography, ion beam structuring and implantation at high speeds in submicron and nanometer dimensions. There are many areas to be investigated and problems to be solved before the technology can be developed to the level of current submicron electron beam lithography (EBL). The ion beam lithography (IBL) processes look inherently superior because the more massive charged particles do not produce backscattering that limits the resolution in EBL and the ions deposit more energy per particle making the resists 50-100x more sensitive to ions than to electrons. With current densities in focussed ion probes that are as large as the current densities now used in EBL, very fast writing speeds and very high resolution structures can be expected. Our work in this program has concentrated to date on the development of the necessary instrumentation that is required to produce high current density probes that can be scanned over substrates under the conditions required for ion beam lithography so we can investigate experimentally the ion-resist and ion-substrate interactions, and determine the sensitivities and resolution limits that can be realized. Actual structures and devices are to be fabricated by IBL with these ion beam systems. Two systems have been designed.

The first field ion probe system, FIPS I, has been designed to use and fit onto the existing H_2^+ field ion source that was developed in our laboratories (1)(2)(3)(4). The design of this system was relatively simple with performance characteristics limited to carrying out the initial investigations on ion-resist interactions, resolution limits and adjacency effects both in patterning and in the processing procedures required to fabricate structures and devices. While the mechanical construction, electronics and stage and substrate handling were kept to a minimum, considerable effort was made to develop a high resolution electrostatic lens system to produce the desired high resolution, high current density characteristics. Also critical factors such as UHV design was used throughout to provide the very clean environment needed for proper source function.

The second system was planned as an ion beam system with some reasonable level of direct write IB lithography capability for direct writing of submicron and nanometer structures and relatively simple device fabrication. With the acquisition of the Hewlett-Packard prototype high speed, high precision electron beam lithography system (HERMES) the goals in our program have been greatly upgraded. We are now developing an advanced ion beam lithography system that could carry out any of the research and development of lithography processes

and device fabrication that are now being carried out by electron beam lithography. In addition, there is the potential of realizing all the significant advantages to be expected with ion beam lithography: higher resolution, no proximity effects, faster writing speeds, utilizationtof better resists, etc. With this system we would be able to structure and fabricate in the nanometer range of dimensions as well as in the submicron range. We have designed a field ion source and ion optical system to replace the existing electron beam system of the HERMES. The major part of the total system can be converted directly to our application to fit the laboratory environment under which the system will be operated. Some of the electronic subsystems will have to be modified. In this report the system, its characteristics and its utilization as an IBL system will be discussed in detail.

PROTOTYPE FIELD ION PROBE SYSTEM (FIPS I)

The prototype field ion probe system that has been designed and built for carrying out our initial observations on high resolution, high current density H_2^+ ion probe interactions with resist and electronic materials is shown schematically in Fig. 1 (5). It is based on using the actual field ion source that had already been developed, built and tested in our initial investigations on high brightness field ion beam sources (1)(2)(3)(4). A chamber was designed and constructed to house the ion optical focussing and deflection system, stage, specimen exchange lock and image intensifier system. These several components and the related development work are described in this section.

Field Ion Source.

Since the source for the prototype Field Ion Probe System (FIPS I) is the same basic source that was developed in our initial work on high brightness field ion sources under NRRFSS, we had hoped to use it without modification. However, tne original design did not function well when raised to the higher voltage (30 kV) that is desired for ourinitial investiations on direct writing in resists with focussed probes. A new source was designed and constructed that fits on the same Liquid He cold finger and into the same housing built for the probe system. A cross-sectional schematic of this new source is shown in Fig. 2.

FIPS I
FIELD ION PROBE SYSTEM

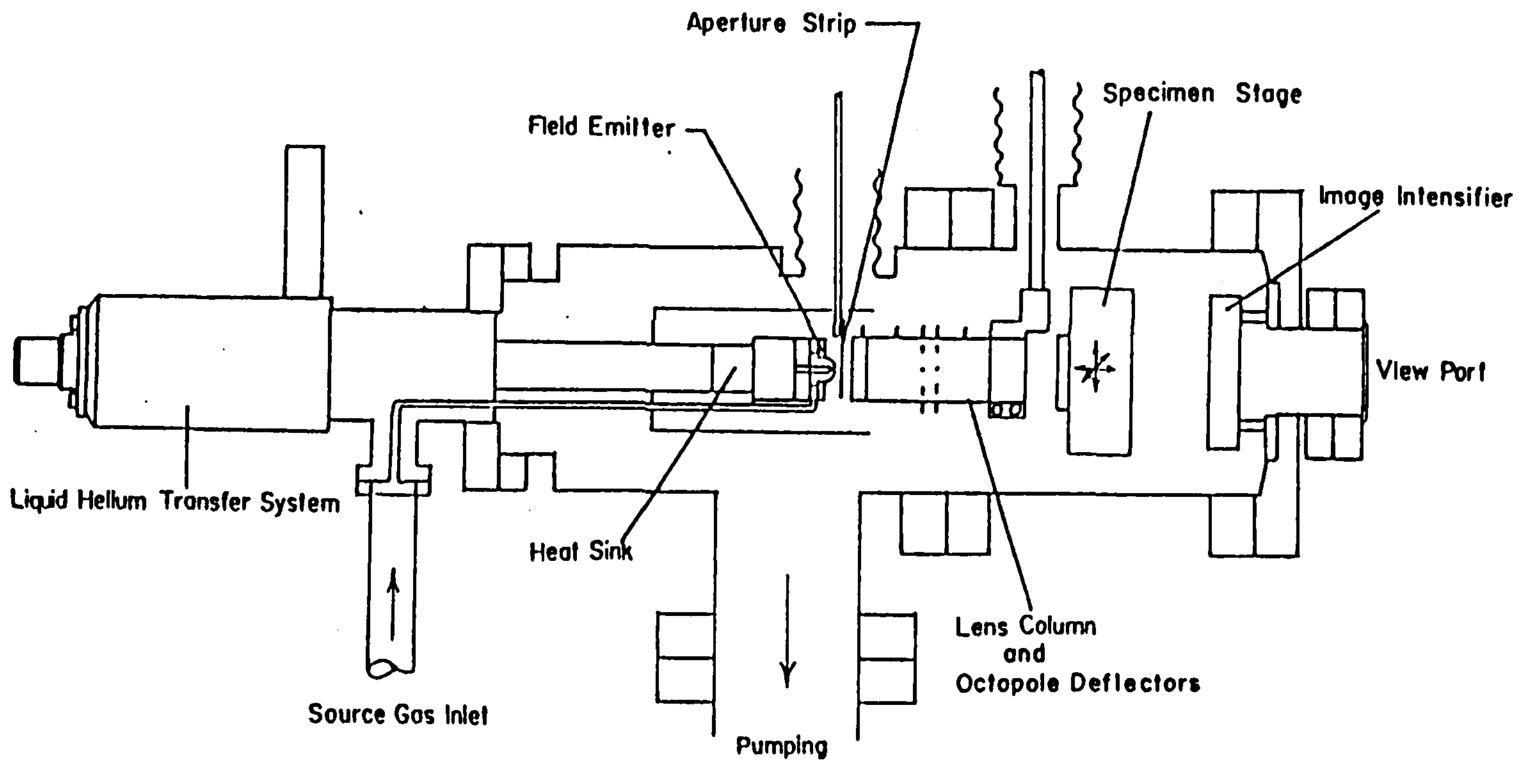
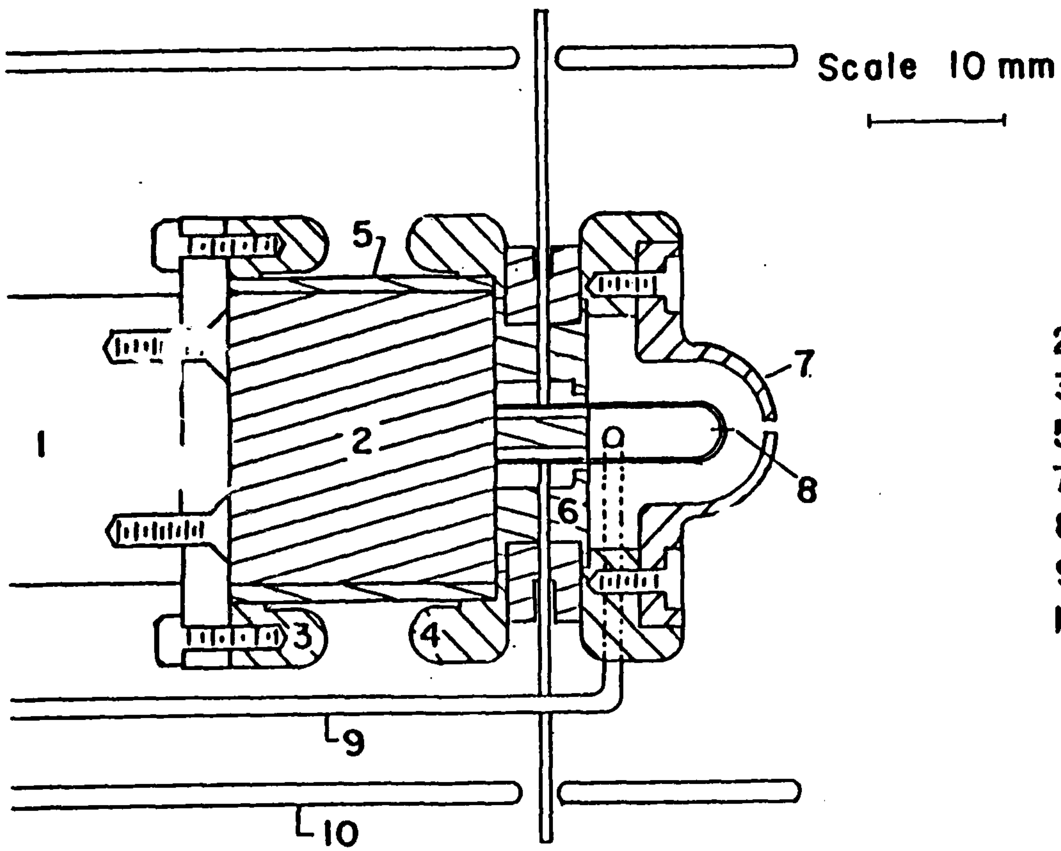


FIGURE I

FIELD ION SOURCE FOR FIPS I



1 HELITRAN
2 SAPPHIRE BLOCK
3,4 Ti CORONA SHIELDS
5,6 MACOR SPACERS
7 CATHODE CAP
8 EMITTER TIP
9 H_2 GAS FEED
10 RADIATION SHIELD

FIGURE 2

The measured characteristics have demonstrated that this field ion source is a very high brightness ion source comparable to field emission electron beam sources. Angular current densities, $dI/d\Omega$ = 10 to 20μamp/sr and can be obtained routinely with energy spread in the beam ΔE = 1.0 eV (1)(2). The emission sites can be very small (5 to 10 Å) giving source brightnesses of ≈ 1×10^9 amp/cm^2/sr at 6 kV. However, in practical applications this beam must be focussed by electrostatic optics that will produce an aberration limited beam. We calculate that the beam focussed to a 100 Å diameter probe and accelerated to 50 eV would have an effective brightness of $\geq 1 \times 10^8$ amp/cm^2/sr.

Ion Optics for FIPS I.

The optical characteristics of the probe focussing system was specified to give a 100 Å diameter probe that could be deflected ± 0.1 mm with an acceptance angle of 2 mr. An electrostatic optical system to meet these specifications was designed using a computer aided design (CAD) method that was developed under this program (6). This software program provides a rapid, interactive method for trying many configurations of equidiameter cylindrical electrodes and octupole deflectors to define a lens system giving the desired optical characteristics. The charged particle trajectories, the optical parameters, aberrations and image figure can be obtained for a set of multiple electrodes in a matter of seconds with this program on a minicomputer (PDP 11/34). Analytical functions are used to approximate the axial potential distributions between cylinders kept at different voltages. We have checked the results using this methodwith the more accurate charge density method (described below) and found that very reasonable agreement is obtained. The first order properties correspond to within a few percent while aberration figures only differ by < 20% (6).

A schematic of the lens configuration developed for the FIPS I is shown in Fig. 3. The lens system consists of five cylindrical electrodes at differing potentials. The first electrode must be kept at the voltage required for field ionization, about -6 kV with respect to the emitter tip. The second and third electrodes make up, together with the first electrode, an asymmetrical triode accelerating lens that is operated to focus the source (actually a virtual image of the emitter tip) at infinity. The third electrode has been configured as a double octupole deflector. This electrode is near ground potential to allow the scan electronics to operate near ground rather than floating the system at high voltage. By using two eight pole deflector systems, a cosine distributed field can be used and the two deflector systems balanced to minimize the deflection aberrations (7). The third electrode together with the fourth and fifth electrodes are operated as an einzel lens that focusses the parallel beam produced by the first three elements onto the substrate surface which, of course, should be at ground potential.

OPTICAL SYSTEM FOR FIPS I

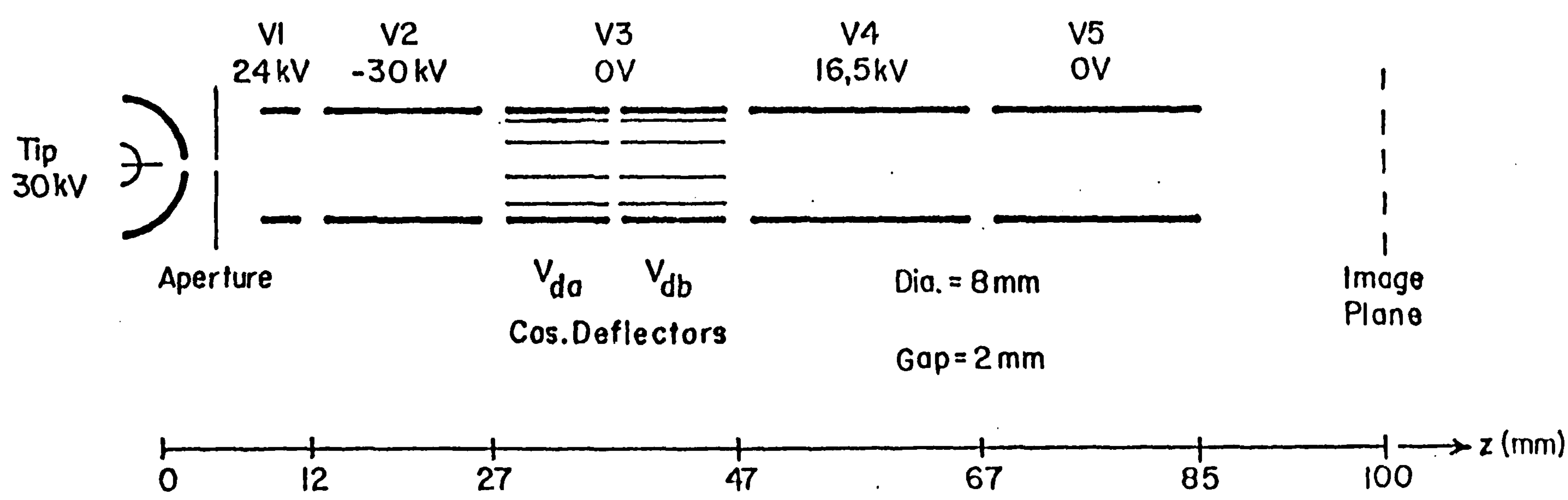


FIGURE 3

A schematic cross-section of the actual lens that has been built is shown in Fig. 4. It is constructed of titanium electrodes separated by MACOR™ insulators. The whole system was machined to fit accurately together and brazed as a unit. Calculations on this lens system indicate that the beam from our sources could be focussed to a 102 Å diameter probe and deflected over a 0.2 x 0.2 mm field (2 x 10^4 beam diameters) without dynamic correction (5). These characteristics are obtained assuming operation under the following condition: acceptance angle α_0 ± 2 mr, 30 keV beam energy with an energy spread of 1 eV. Taking the measured angular current densities that we have obtained with our H_2^+ source of $dI/d\Omega$ = 10 amp/sr and 20 amp/sr, the current density in this 102 Å diameter probe would be 150 and 300 amp/cm^2 respectively. This optical system has been built and incorporated in the FIPS I system as shown in Fig. 1.

Work Chamber.

A work chamber was built to house the centerable, limiting aperture, the ion optical and deflector system, the movable stage, the specimen exchange lock and the image intensifier for viewing the beam. The lens holder allows limited alignment of the lens system. The stage has X,Y and Z motion activated by linear and rotary vacuum feed-thrus controlled by external micrometer screws. A UHV vacuum valve moves the stage to the loading position and provides a vacuum seal to allow specimen exchange without bringing the whole system up to atmospheric pressure.

The image intensifier (CEMA), based on a channel plate electron multiplier with a fluorescent screen, allows viewing of the beam as it is focussed and scanned. The beam current can also be monitored with the CEMA. By deflecting the beam across orthogonal knife edges at the specimen stage and monitoring the current to the CEMA the probe diameters can be measured.

Electronics for Octupole Deflectors.

We have designed, constructed and tested the electronic system required to drive the double octupole deflectors that scan the beam. Fig. 5 shows a block schematic of the electronic system. The input to this system can be either digital or analogue to produce the scans required to have the beam write the desired field. The voltages are adjusted by the summing networks to produce a cosine distribution on

OPTICAL COLUMN AND DEFLECTORS FOR FIPS I

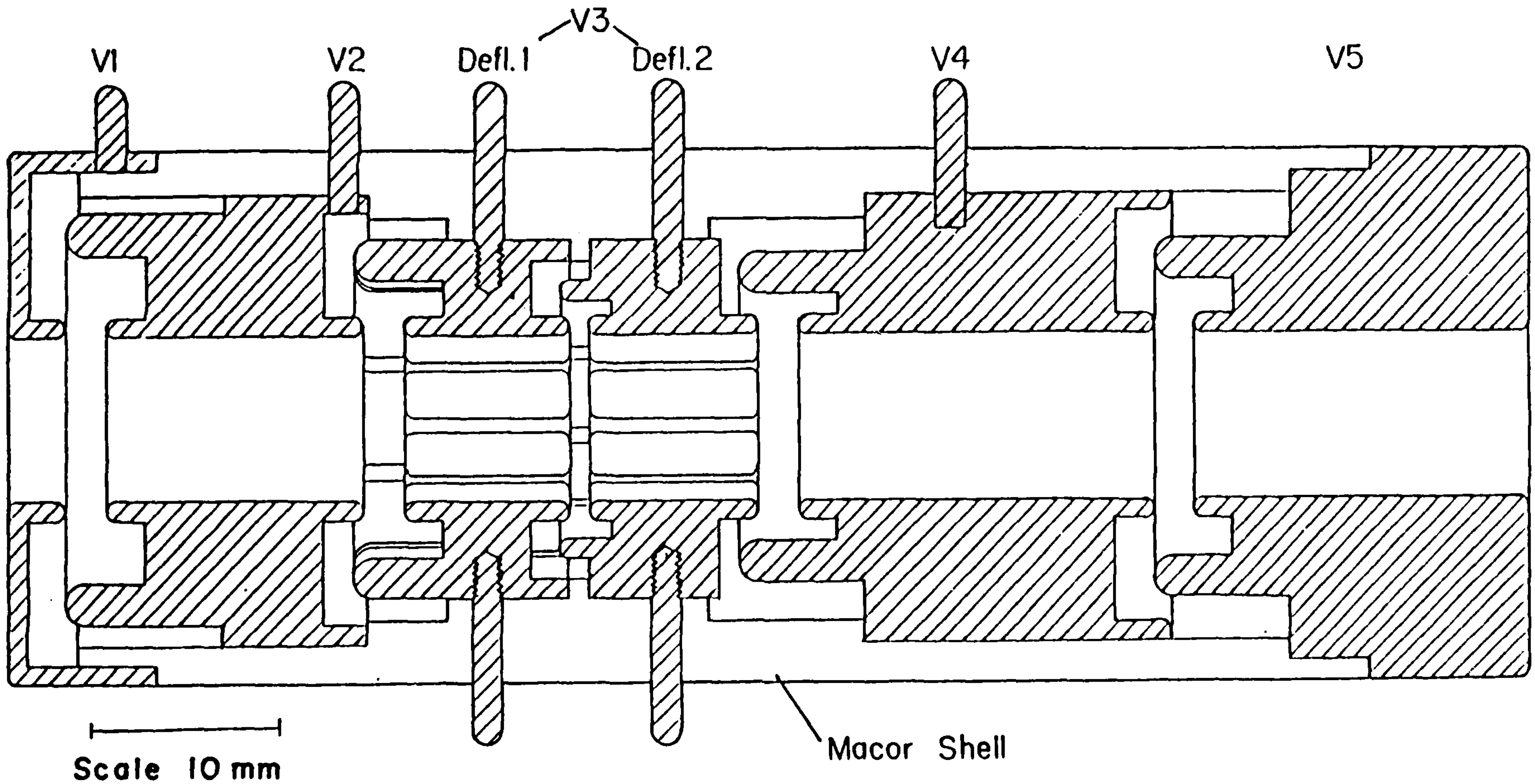


FIGURE 4

ELECTRONICS FOR FIPS I

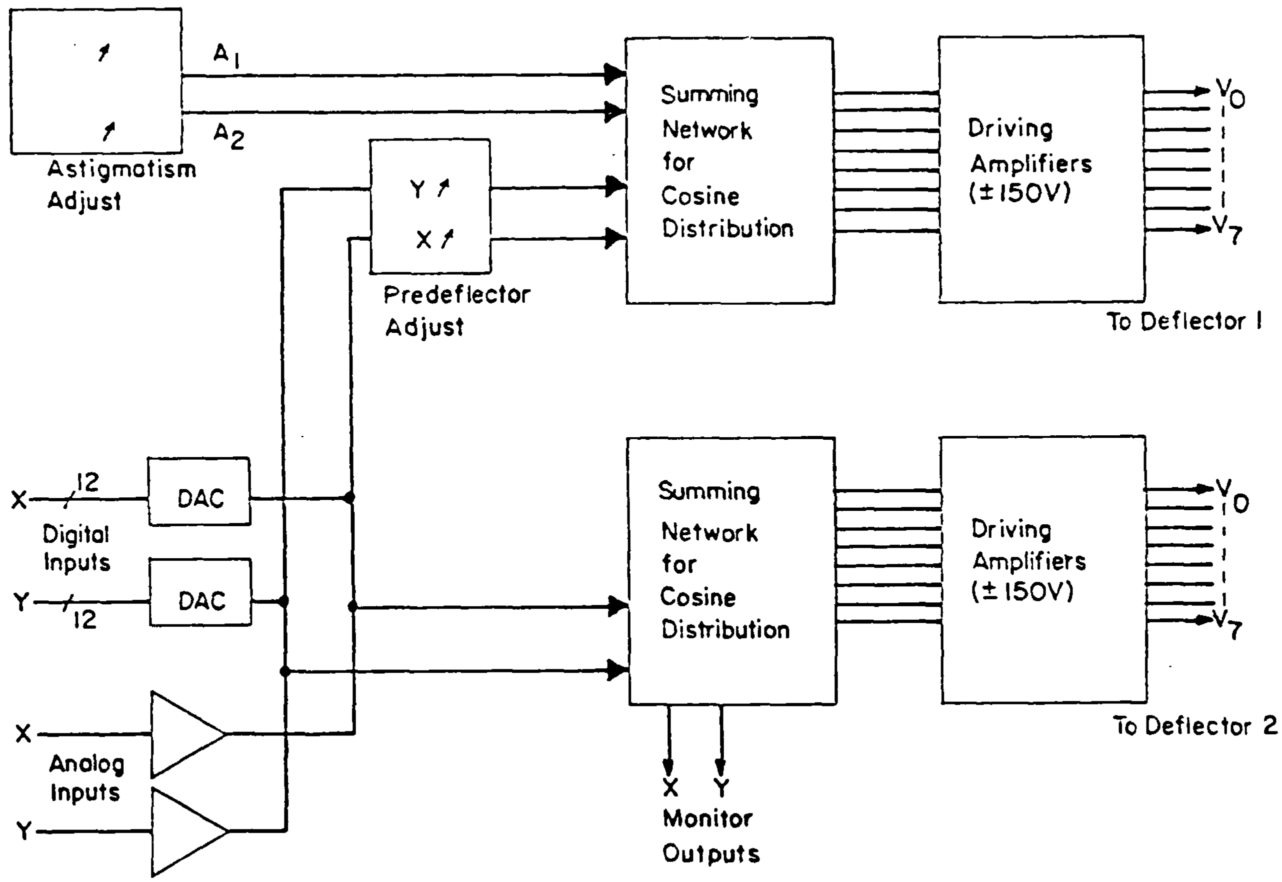


FIGURE 5

each of the octopule deflectors. High voltage op-amps are used to drive each pole at the correct voltages up to ± 150 volts. Additional D.C. voltages can be applied to the electrodes of the first octupole system to correct for misalignment of the beam and astigmation in the optical system.

Progress on bringing the FIPS I up to an operational level has been disappointingly slow. Until the past summer this task has been the responsibility of one graduate student Research Assistant with part time help from a Research Specialist. While the system was designed and constructed in good order, many detailed problems were encountered trying to get it functional. In September a Postdoctoral Associate joined the project and in October a new Research Specialist was taken on. Both are now assigned to work on this task jointly with the graduate student and progress has been much accelerated. A new source has been designed and built (Fig. 2). Its cryogenic behavior has been tested and is satisfactory. This source has been taken up to 30 kV without encountering any of the high voltage difficulties of the old source. As soon as we have characterized the beam, the ion optics will be inserted in the chamber and a focussed probe obtained. Unless serious difficulties are encountered, we hope to have this system running, tested and characterized by the end of the year.

THE ADVANCED FIELD ION PROBE SYSTEM FOR ION BEAM LITHOGRAPHY

The program as originally proposed called for the design and construction of a field ion probe system of relatively simple design that would have the necessary basic components to produce a high resolution, high current probe which could be scanned at moderate rates with rapid blanking to give well controlled exposures. The work chamber and stage, also of relatively modest design, would have specimen and wafer handling capabilities to allow lithography processing and structuring of simple devices at submicron and nanometer dimensions (10-100 nm).

Work on this system had proceeded to the point where both an advanced ion optical system had been developed using CAD (computer aided design) and a field ionization source for this system had been designed. The basic ion beam column was thus designed. At this point a major new acquisition was obtained that has greatly enhanced the

potential capabilities that we can realize in our program for Ion Beam Lithography (IBL). The P.I. negotiated a gift from Hewlett-Packard of one of their prototype, precision, high-speed electron beam lithography systems (called HERMES by H-P.). This system is a very advanced, state of the art instrument with a 300 MHz data rate, very high precision, laser interferometer controlled stage, all under the control of an H-P 1000F computer system. This sophisticated electron beam system was given to the School of Applied and Engineering Physics at Cornell specifically for the P.I.'s program in ion beam lithography. The system has been appraised at $750,000.

With this greatly enhanced capability for the development of a lithography system with specimen handling and processing that is comparable to the most advanced electron beam lithography system, our program goals and schedule were modified to take advantage of the great potential that we now have available. The H-P HERMES system will be converted to an ion beam lithography system by replacing its electron beam field emission source with the H_2^+ field ionization source we have developed and designed and replacing the magnetic electron lenses and column with the electrostatic ion optical lens system we have designed. In this report the HERMES system will be described in some detail and the subsystems and capabilities of the instrument that can be utilized in our IBL system will be discussed. The modifications that will have to be made and the present status of our design work on the modification will be detailed. The Field Ion System (FIPS II) based on the utilization of the H-P instrument will be designated HERMES II.

THE HEWLETT-PACKARD PROTOTYPE EBL SYSTEM: HERMES.

Figure 6 is a block schematic of the system architecture of the HERMES and should be referred to in the discussions that follow. The Electron Beam System that Hewlett-Packard developed based on the HERMES prototype has been described in some detail in several articles in the May 1981 issue of the H-P Journal (8).

System Architecture of HERMES

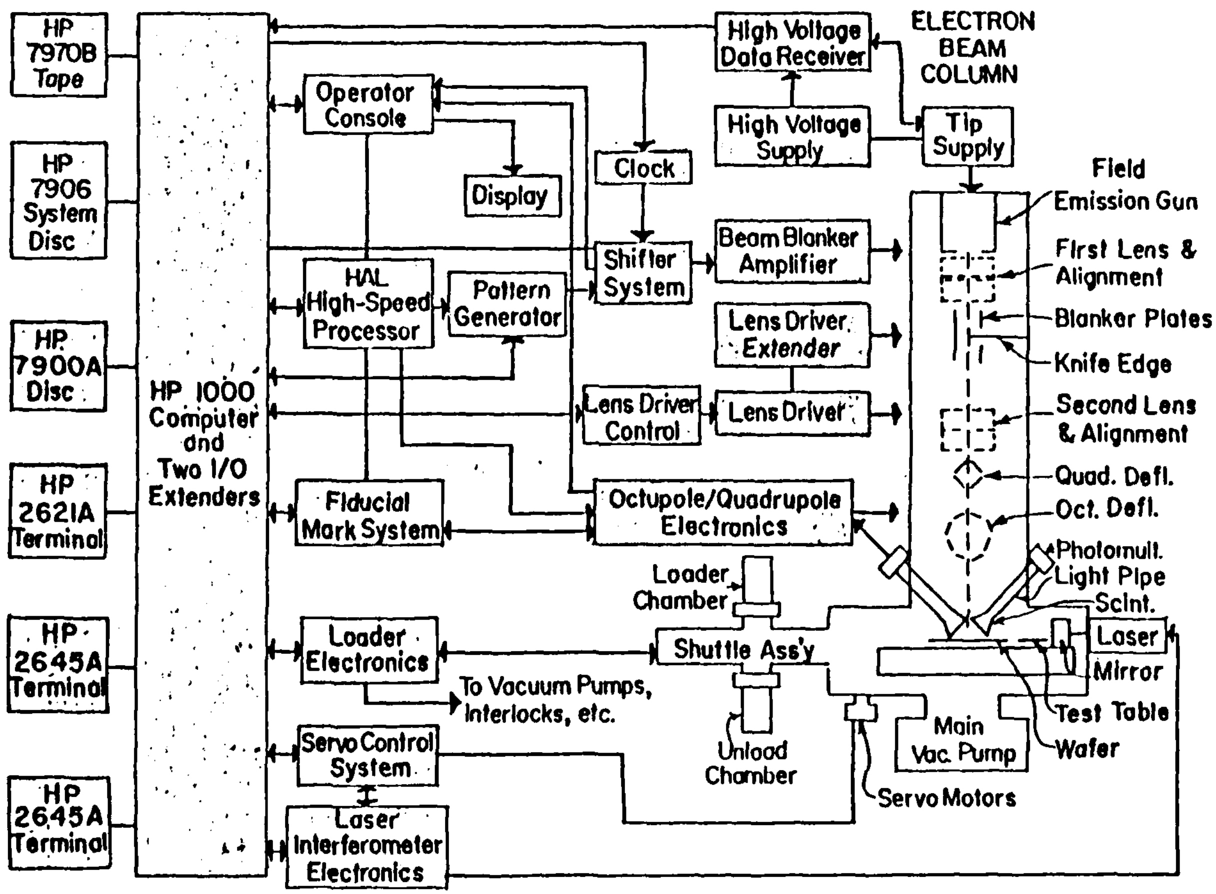


FIGURE 6

Electron Beam Column.

A highly schematized representation of the electron beam column is shown on the right side of Fig. 6. This electron optical system is the main component of the HERMES that must be modified in the conversion of the total system to an ion beam lithography system. There are, however, several very significant components in the EB system that can be utilized for the ion beam system, and in any case, the functions of the EB column must be understood to follow a detailed description of the HERMES.

The electron source is a field emission electron gun that uses a zirconiated tungsten filament operated in the T-F (thermal field) emission mode to produce a beam with very high angular current densities, relatively low energy spread and consequently very high brightness. The beam is focussed by magnetic lenses to a 0.5 µm diameter probe on the substrate with a current density of about 40 amp/cm^2. In the later model, developed by H-P on the basis of the HERMES prototype system, the electron optics have been improved to give 0.5 µm probes with current densities of 300 amps/cm^2 (9)(9a).

The conversion of this electron beam column to an ion beam column will require replacing the field emission source with the field ionization source that we have developed. Since both systems operate under UHV (Ultra High Vacuum), we can use the very extensive UHV vacuum system capabilities that are contained in the HERMES. The magnetic lenses that focus the beam will have to be replaced by an electrostatic lens system since the magnetic lenses do not have the refractive power needed to focus the heavier charged particles, H_2^+ ions, that are used in our beam. Electrostatic refraction of charged particles is independent of e/m so the same optical properties can be obtained with electrostatic lenses in focussing ions and electrons. The ion optical system we have developed and proposed to use in the ion beam column will be described in detail in a later section.

The H-P system does have several electrostatic components in the EB column and these can be used with a minimum of adaptation in the IB column. Electrostatic systems are used for beam alignment, correction of astigmatism, beam blanking, and scanning of the beam. The HERMES column has both quadrupole deflectors for patterning 64x64µm subfields and an octupole deflector system for accurately positioning the beam in 80x80 subfields to produce a 5x5 mm square pattern before the stage must be moved for step and repeat patterning. These electrostatic systems will be adapted to the IB column. Though the physical dimensions of the components will have to be scaled to our higher resolution and higher energy beam requirements, the basic systems can be used.

The whole EB column mounts on the top plate of the main vacuum work chamber through an 8" i.d. port. It will be a straightforward design problem to have the IB column we build replace the present EB column.

Mechanical and Vacuum Components.

The mechanical and vacuum components will be described in some detail (10) since all of these components can be used directly in our IBL system, HERMES II. While some of the substrate handling capability is designed for large capacity through-put of wafers in a production environment which we do not need, we can utilize the existing system at any level appropriate to our needs without modification.

Precision X-Y Stage.

Crucial to the performance of a lithography system is the accuracy with which the substrate to be exposed can be positioned relative to the area to be scanned by the beam. The H-P system has a very high precision stage monitored by three laser interferometers. The stage is constructed with a design assuring high mechanical stability and reliable movement. The key mechanical components are mounted on a thick (50 mm) horizontal steel plate. The column is placed on the top face of the plate and the stage and associated interferometers are attached to the bottom face. This plate is also the top wall of the main vacuum chamber. This design is readily adaptable to our ion beam system. We will only have to match the ion beam column to the base plate part in which the electron beam column now sets.

Special lead screws and drives have been designed to provide backlash free drives for the closed-loop servo system. To make this system compatible with the vacuum environment, the servomotors that drive the X and Y motions of the stage are mounted ouside of the vacuum chamber and the shaft motion is transferred through the chamber walls via ferromagnetic-fluid shaft seals.

Three plane-mirror interferometers, modified for a high vacuum environment, are used to measure stage location: one for X, one for Y and one to measure small amounts of yaw. The X and Y interferometers are placed on the 50 mm steel plate as close as possible to the axis of the column and mounted so that measurements are made perpendicular to the plane mirrors and aligned with the column axis to reduce the error off-set.

The X and Y interferometer mirrors are mounted orthogonally within a fraction of an arc-second to a titanium "home plate" that is secured to the X-Y stage by flexible mounts that hold the home plate slightly above the stage. The X-Y mirrors are flat within an eighth of a wavelength. These tight tolerances are required to achieve the final position error of less than 160 Å (0.016 μm).

Substrate Mounting on the Home Plate.

The accuracy of the beam system is influenced by the stability of the substrate position with respect to the stage. All substrates are mounted in frames or "pallets" with respect to their top surface. Wafers are contacted by the pallet about their entire circumference. Great care was taken to assure that the X and Y motions are orthogonal and coupled closely to the pallet assembly.

The pallet is placed on the "home plate" (labelled Test Table in Fig. 6) and the location of the pallet is determined by five points: three gravity-load horizontal pads and two pins that engage a vee and a flat on the pallet edge. The pallet is held against these pins by a spherical contactor and toggle mechanism.

Also located on the home plate are targets which permit calibration of the beam-deflection system using the SEM mode (described below) and a Faraday cup for beam current measurement. Height pads are a part of the calibration system. These permit checking the operation of the height sensors which are four capacitive transducers mounted in a square pattern on 25 mm centers attached to the lower part of the column. The height sensors determine the height and attitude of the wafer or substrate so the deflection magnitude and focus of the beam can be adjusted. This allows positioning the beam pattern within $\pm$ 0.07 μm without requiring mechanical adjustment of the distance between substrate and column to within unattainable tolerances. The height accuracy that these sensors give will be well within the requirements for focussing our IB system for high resolution probes.

Loader System.

The loader system delivers the pallets to the X-Y stage and retracts them after exposure. The system, designed for a production environment, consists of three chambers each containing separate mechanisms and having a substrate handling capacity many times in excess of our IBL needs during the experimental and developmental stages. However, all the automatic substrate loading and exchange and vacuum capability in this system can be used to great advantage in our IB system at whatever level we find useful.

The pallets are mounted in cassettes that can hold up to ten pallets each. The cassettes are passed in and out of the "shuttle chamber" via two 25.4 cm gate valves which are used as air locks to the load and unload chambers. The cassette position is monitored by infra-red LED detectors and locate the desired pallet on the shuttle mechanism. Once a pallet has been initially positioned, it is delivered to the home plate on the X-Y stage. After exposure of the substrate the pallet is removed by the shuttle mechanism and delivered to the unload chamber.

Vibration Isolation.

An important part of the mechanical design of the HERMES is the extent to which vibration isolation has been achieved. The concept of fastening the critical components to the thick steel plate eliminates, to a great extent, the need for placing the system in a seismically quiet environment. But additonal care has been taken to isolate the system from vibration in the laboratory environment. Vertical vibration is adequately reduced by simple, air-filled rubber vibration isolators under each of the four legs. Horizontal vibrations are a more serious factor in deteriorating the performance of a system of this type. Horizontal vibration isolation is provided by externally pressurized air bearings placed between the floor and the vertical isolators. The whole system floats on air cushions flowing between precision ground steel plates. A separate air compressor located far from the system provides the 100 lb/sq. inch pressure required.

One component of the vacuum system is a cryopump that evacuates the load and unload chambers. The compressor of this pump produces vibrations that could be a serious problem and must be isolated from the system. This isolation is accomplished by mounting the pump on a massive iron plate in direct contact with the floor and eliminating vibrations through the vacuum manifold by using one horizontal and one vertical section of 8" diameter pipe with each section having flexible bellows at each end. A roller-bearing universal joint built around each bellows prevents collapse when an atmospheric load is applied upon pump down.

Vacuum Systems.

In modifying the HERMES to an IBL system, all of the extensive vacuum components can be utilized. The field emission gun system uses four 30 liter/sec Vacion pumps to obtain the UHV required for stable field emission. The UHV and clean environment required for the field

emission system is maintained by separating its volume from the rest of the column by a small aperture so the source and column are differentially pumped. The column is differentially pumped by a 30 liter/sec ion pump. These pumps and their separate controllors can all be utilized on the IB source and column we construct. There is a specially designed double valve in the column that allows the upper part of the column to be separated from the lower part so the filament in the gun system can be changed without bringing the whole system up to atmospheric pressure. Unfortunately, this valuable valve requires too long a distance along the optic axis for us to incorporate it in our column.

The work chamber is evacuated by a large, 400 liter/sec ion pump and, of course, will remain part of that whole system which will not need modification. A 25.4 cm diameter gate valve can be closed to separate this ion pump from the work chamber. The load and unload chambers are evacuated by a large cryopump (8" diameter) that provides for a very rapid pump down of the substrate exchange system. Two 25.4 cm diameter gate valves isolate these loading chambers from the shuttle chamber.

All of the vacuum systems are roughed down to a pressure low enough for the ion pumps to take over by a Varian Megasorb station. This sorb pump system can be attached to different sections of the column and work chamber through several different ports that are sealed off by high vacuum valves.

Computer Control and Electronics.

Fig. 6 should be referred to in the following descriptions of the architecture of the computer control system and the variety of special purpose electronic subsystems used to drive the beam, control the data and activate the mechanical systems (11).

Computer Control.

The overall system coordination is accomplished via the host computer, an H-P 1000F. This machine is a 16-bit computer with extended memory and input-output extenders for the many peripheral controllers. It is used somewhat as a process controller since all of the beam control, deflection control, data handling and analog processing are done with special purpose hardware designed specifically for the HERMES system and are under the command of the H-P 1000F. The large number of peripheral controllers require the addition of I/O extenders. Attached to the computer are two disk drives, a magnetic tape for system back-up

and program transfer from other machines and three terminals to enter operator commands and monitor the status of the system.

Scanning Electron Microscope (SEM) Mode: The Operator Console and Fiducial Mark System:

The HERMES can be operated as a Scanning Electron Microscope (SEM) by detecting the backscattered electrons as the primary beam is scanned in a raster over the substrate area to be observed. This mode of operation is used for electron optical beam alignment, focussing and stigmating the beam. This mode is also used to observe the fiducial marks that are used to locate and set the desired positions on the wafer for pattern registration and calibration.

The operator console is the interface between the operator and the system when it is run as a scanning electron microscope. Inside the console are I/O controls and front panel sections that monitor various read-out modes, displays, magnification, etc. The operator console also generates the analog signals sent to the display system. The signals are derived from signals received from other parts of the system. All incoming signals are either optically isolated or isolated by high impedance buffers to break up system ground loops.

A Fiducial Mark System is used to locate the substrate with respect to the beam. The signals either from the photomultiplier or a Faraday cup go the preamplifiers, each of which has a 12 bit DAC that can zero the output of the pre-amp under control of the H-P 1000. The outputs of the pre-amps are sent to a conditioner section where they are summed or differenced with provision (via a DAC) for nulling the result. Selection is made among the individual pre-amp outputs, the sum, the difference, or ground. The selected signal is sent to the integrator and the buffer. The buffer convertsthe single-ended analog signal into a differential signal and transmits it to the operator console. This analog signal is used by the CRT display in the SEM mode.

The integrator provides the ability to average the input signals from the detectors over a period of time to obtain the necessary signal to noise required to accurately locate the fiducial marks. Correlating the occurrence of the signal caused by the mark with the deflection voltages required to position the electron beam at that location establishes the pattern coordinates.

The operator console can also be used to control the stage and send it to a desired address entered by the operator on to a pre-stored address. The stage address and octupole address are displayed on this console as well.

All the functions and control capability described in this section can be carried over to the ion beam system (HERMES II). The only modification required will be changing the detector system that observes the backscattered beam incident on the scintillators in the HERMES to a detector system that will monitor the low energy secondary electrons produced by the primary ion beam as it scans the substrate. We have observed that the H_2^+ ion beam that we will use produces secondary electrons in numbers approximately equal to the number of primary ions in the beam. Collectors will be designed and built to accelerate these secondary electrons to an energy that produces efficient photoemission from the scintillators. The same photomultiplier system and all the related electronics can then be used.

The HAL System, Pattern Generator and Deflector Electronics.

High Speed Processor, HAL.

The high data rate (300 MHz) requires numerous, very rapid calculations to determine the voltages that must be placed on the octupole plates in real time during exposure to make the dynamic corrections as the beam is deflected to each of the 80x80 subfields that make up the 5 mm x 5 mm field. To accomplish this task H-P has built a special purpose high speed processor called HAL, implemented with emitter coupled logic (ECL). It is microprogrammed and can execute a program of 512 steps. The microcode is generated using an assembler and is down loaded from the H-P 1000F host computer. This allows flexibility in controlling the beam deflection protocol since changes can be made in a straightforward manner. HAL is built around several bases and the architecture allows considerable flexibility in modifying or inserting new instructions.

HAL, based on ECL, is a very advanced electronic system and we are now studying it to determine whether or not we want to use and maintain this system. The lithography processing that we wish to do with the IB system does not require the high speed patterning for high through-put that is needed in a production environment. We are evaluating the best methods for utilizing the HERMES capabilities without committing ourselves to such advanced electronics systems.

Pattern Generator.

The pattern generator in the HERMES is not satisfactory for our use. We are advised by H-P that this pattern generator is an obsolete system that would be very difficult to maintain and for which software support would not be available. We have analyzed the circuits of this pattern generator and defined the elements of the system that we wish to retain. We plan to design and construct a pattern generator system that will be compatible with the other pattern generators that are being used in the National Research and Resource Facility for Submicron Structures (NRRFSS). Patterns are developed in NRRFSS using the Aplicon for CAD and we plan to use this system.

Deflector Electronics.

The HERMES uses a dual deflection system. Small subfields, 64µm x 64µm, are scanned rapidly in a raster using a set of four electrodes (quadrupole). Then the beam is accurately positioned with all the necessary dynamic corections to the next subfield by the eight pole (octupole) deflector. The 5 mm x 5 mm field pattern is thus divided into 80 x 80 subfields. Since the system is using a 0.5µm diameter beam probe there are 128 x 128 pixels per subfield and 10^8 pixels per total field. We are evaluating this scanning mode and will decide how best to use the very advanced scanning capability in our IBL system. While we do not need the high through-put available with this dual system, we can adapt much of the electronics to the level of our needs for high resolution scanning over smaller areas. The actual physical deflector electrode systems will not fit into our column design but they are electrostatic deflectors and so the deflector electronics can be fully adapted to our needs by designing and constructing electrode configurations that would require the same driving voltages as the system in the HERMES.

Quadrupole Electronics.

The quadrupole electronics generate raster-scan voltage waveforms for driving the quadrupole deflection plates which electrostatically deflect the beam. The quadrupole electronics also provide for magnifying and rotating the raster. The deflection waveforms can be generated over a five-decade range in operating frequencies. The electronics consist of two independent ramp and step generators with each generator responsible for the waveform for one pair of quadrupole plates.

To accommodate the wide range in operating frequency, three separate integrator, summing amplifier and inverter sections are used, each

optimized for operation over one or two decades. The outputs of the various amplifiers are then selected by multiplexers for final presentation to the deflection plates. The final waveforms generated by the quadrupole electronics are linear within better than 0.1% over the ± 4 volt deflection range required for a 64 x 64μm block scan. The raster scan signals are compatible with a 3 kHz to 300 MHz, 0.5μm-step data rate.

Octupole Electronics.

The voltages required by the octupole deflectors are generated by eight amplifier-DAC combinations. To deflect the beam over a 5 x 5 mm field a ± 80 volt capability for each deflector plate is required. Since the system's accuracy and speed are directly affected by the octupole's accuracy and speed, considerable care was taken to maximize these parameters. Accuracy is obtained by using DAC with the highest accuracy available. The best commercial units achieve 16-bit long-term stability and 17 to 18 bit short-term. The settling time for these DAC's is a few microseconds.

To convert the DAC current of 0-2 mA to the ± 80 volt signal, a high voltage amplifier with an 80 kΩ feedback resistor is used. Placed between the amplifier and the DAC is a cascode circuit. The cascode circuit increases the impedance seen by the amplifier and reduces the noise gain in the high voltage amplifier to unity. With this circuit the overall performance (accuracy and settling time) is determined by the DAC rather than the cascode or the high voltage amplifier.

Interferometer and Stage Control Electronics.

The motion of the X-Y stage is controlled by two-axis stage control systems. The X-Y position is monitored by two laser interferometers with a third interferometer used to monitor the rotation of the stage. The interferometer electronics processes the interferometer signals to obtain outputs of position and position error. This electronic system, consisting of an arithmetic/logic unit, fringe counter and control logic, achieves resolution of 80 Å and is able to track stage motion up to 10 centimeters.

Servo electronics receives a 28-bit position error signal from the interferometer electronics and drives the motors that move the stage. The position error signal is truncated to 14 bits plus sign and displayed on the operator console. The truncated error signal is converted

to an analog voltage by a special DAC which achieves precise voltages near zero. Under the H-P 1000F computer the servo electronics can be operated in the following modes:

1) Slew at constant velocity in both positive and negative directions.
2) Brake or coast.
3) Position control.

The control logic of the servo electronics selects the appropriate input and feedback signals. In the position control mode the system settles to less than 0.1μm error from a 5 mm step in less than 250 ms and the final position error is less than 160 Å.

This high accuracy of control will be vert useful in our IBL work. We do not need the large stage motions but as we develop high resolution capability with ion beam patterning, we can take advantage of this very advanced stage mechanism with its high stability and the accuracy to which it can be positioned. Step and repeat methods can be used to stitch fields together to overcome the limitations set on deflection distances by aberrations in the ion optical system.

Loader Electronics.

There are loader electronics available to move wafers in and out of the system and activate the required valving sequence. There is also an over-ride mechanism that provides operator control of this process. In practice for the single wafer throughput that we will require for some time, we may not use the software that allows computer control of this process.

CONVERSION OF THE HERMES TO AN ION BEAM LITHOGRAPHY SYSTEM.

The conversion of the HERMES EBL system to the HERMES II IBL system requires a careful evaluation of the characteristics and capabilities we wish to realize in our laboratory Ion Beam Lithography System. Our system will be used for research and development rather than for high through-put of wafers or masks that have been configured for VLSI fabrication in a production environment. A careful and thorough systems

approach must be used as specifications are set for the performance level of the total system and what modifications must be made in the subsystems of the existing EBL system. It is important to factor in what capabilities are necessary and/or desirable and the constraints and limitations on us in realizing these goals.

Present Status.

The HERMES arrived in Ithaca in July 1982 and was reassembled and is being brought up as an electron beam system to test the performance of the various subsystems. Before disassembling the system in the H-P Laboratories in Palo Alto, we tested the system in the Scanning Electron Microscope (SEM) mode. This mode utilizes almost all of the electronic systems at some level and will enable us to check out the individual electronic subsystem and the electron beam column performance.

The total instrument has been reassembled in a room that was remodelled slightly to accommodate the linear arrangement of the system which requires a 30 foot long room. We have been bringing up the various subsystems and almost all of the sections are operational at the time of this writing. This procedure has required considerable learning and diagnostic work and is informing our decision on the modifications that we will make.

The H-P 1000F host computer is up, functions well and is under a service contract with H-P. Most of the electronic sybsystems under the control of the H-P 1000F are functioning as is the laser interferometer controlled stage. At this time we are still working on the special very high speed processor, HAL, and the pattern generator system. These two systems were specially developed by H-P to achieve the 300 MHz data rates required for the high through-put in production. One of the decisions that must be made is what if any of these two subsystems should be retained for our laboratory research instrument.

The HERMES is to be maintained as an EB system until construction of the field ionization source and the ion optical column have been completed and are ready to replace the electron beam column. During the construction period the modifications to the electronic subsystems can be made and tested with the EB system.

The Ion Beam Column.

The major design and construction work that must be carried out to convert the HERMES EBL system to the IBL system, HERMES II, is the replacement of the field emission electron gun source with our gaseous (H_2^+) field ion source and mounting this source on a new column designed to house an electrostatic ion optical and deflection system with all the necessary auxiliary components required to make it a practical IB probe system.

Gaseous Field Ion Source for HERMES II.

We have developed a basic schematic design of the source based on the results of our work with the new source built for the FIPS I. We have not started to prepare detailed shop drawings of this source because a very different approach to source design is now being investigated by G. Hanson under the NRRFSS program. He has just completed the construction phase of that source and is now testing it. He will be studying the performance of the H_2^+ source at temperatures down to 4.2°K and with emitter configurations quite different than the built-up tips that we are using. Before committing ourselves to the design we have developed, we want to have the results of this new work, even though the design we have should be quite adequate for the IBL system we are planning for HERMES II. Our current design would provide a satisfactory source using a built-up emitter tip that could be operated up to 50 or 60 kV and produce reliable beams with angular current densities of at least 10 to 20μamps/sr with energy spreads of 1 eV. Careful design considerations have been made to avoid voltage breakdown or instability caused by field emission from cathode surfaces and/or electrode-insulator interfaces. Good cryogenic design has been used to ensure cooling of the emitter tip to temperatures considerably lower than those obtained in the FIPS I source.

The source is designed to operate in a UHV environment, pumped by 2 or 4 ion pumps that are now on the HERMES field emission source. The source chamber will be differentially pumped to assure a clean environment for the emitter. The emitter tip must be processed to obtain the configuration needed for the high angular current density with a good H_2 supply to the emission site by surface diffusion. Another UHV system available in our laboratory, will be used as a processing station. When a new emitter tip is to be installed in the source, this station will be used to check the source for tip alignment, to process the tip and to observe the beam before moving the source to the ion beam column.

Ion Beam Optics and Deflection System.

Given the source characteristics available, the design of the ion optical system critically determines the performance of the total system as an ion beam lithography system. Therefore, a great deal of effort has gone into the design of the ion optics that we have developed for the HERMES II IBL system. Since we are developing an instrument that will be used to investigate IBL over a wide range of parameters, a flexible ion optical system is required. The performance characteristics that we have set for the probe system are:

1) probe diameters from 0.1μm to 10 nm
2) deflections $\approx 10^4$ beam diameters
3) probe current densities $\approx$ 25 to $\geq$ 100 amp/cm^2
4) beam energies 20 to 60 keV
5) blanking to give exposure times of a few nanoseconds

The given parameters are (1) the source produces an H_2^+ ion beam with an angular current density of 10-20μamp/sr and energy spread of = 1 eV, (2) a field ionization voltage of -6 to -10 kV with respect to the emitter is required, (3) the tip must float up to the positive potential of the desired accelerating energy of 20 to 60 keV so the final electrode, stage with substrate and column can be at ground potential.

Lens Configuration.

There are a number of conditions that must be met in the design of the optical system. There must be at least two lenses with the first lens focussing the beam to a cross-over that is an image of the source. The distance between the tip and the first electrode of the first lens must be at least 6 to 8 mm to allow room for the radiation shielding in the cryogenic design of the source. There must be an adequate distance between the first and second lenses to place the blanking plates as well as alignment deflectors and stigmator. If post-lens deflection is used there must be a working distance long enough to accommodate the deflectors and give an adequate deflection distance without seriously degrading the beam.

A large number of lens configurations and combinations were tried using computer aided design (CAD). The charge density method was used to calculate the axial potential and a program was developed (12) for the computer system available to us (Prime 400). Munro's (13) ray tracing program was adapted for our calculations. With these programs we investigated a wide variety of lenses.

In our system we have a fixed object position (emitter tip) and must focus this source at the fixed image position set by the location of the blanking aperture. If the system is to be operated with fixed

object and image distance at varying accelerating beam voltages (the "zoom" mode) the lenses must have enough electrodes with freely adjustable voltages to meet the required conditions. An additional constraint is the requirement that there must be a fixed field ionization potential so that even at different tip voltages, the voltage difference between the emitter tip and cathode (which is at the same potential as the first electrode of the first lens) does not change. To achieve the "zoom" imaging, we use lenses with four electrodes in an asymmetric configuration. The voltages on the two central electrodes are varied independently to produce good image figures (low aberration) and meet the physical constraints imposed on the system.

The first lens in the system becomes the critical lens that sets the beam acceptance angle and aberration figure limits. The second lens is matched to produce the desired probe characteristics for direct write structuring and lithography. In developing the first lens we found that we could design an electrostatic lens with accelerating electrodes that gives a substantially better lens than has been previously reported. The results of this lens design has been reported (14).

A schematic of the ion optical system that we plan to construct for the HERMES II is shown in Fig. 7. The scale and the physical locations of the components are indicated on the scale at the bottom of the schematic. The bore diameters of each electrode are given in mm on the schematic. The first lens consisting of electrodes V_1, V_2, V_3 and V_4, focusses the virtual image of the emitter tip to a cross-over at the blanking aperture. The tip is placed 8 mm from the first lens electrode to provide room for the field ionization cathode, radiation shield and the aperture that defines the maximum beam acceptance angle that will be used with this optical system. If the system is to produce an ion probe with an energy of 50 keV, the tip would be set at +50 kV with respect to V_4 which is kept at ground. The critical field at the emitter site must be 1.5 V/A if the H_2^+ source is to operate with the low energy spread in the beam of $\Delta E \approx 1$ eV (FWHM). With the built-up tips that are being used at this time to obtain stable emitters, the field is obtained with a voltage difference of $\approx$ -6 kV between tip and cathode. We foundthat we could obtain superior optical characteristics with this lens if V_2 was operated at an accelerating potential, e.g., 75 keV for a 50 keV beam at the substrate. The beam is decelerated in V_3 but again accelerated to the full 50 keV energy by V_4. This configuration gives very superior characteristics, particularly when operated at short object distances. If the constraints imposed by the radiation shielding needed for the cryogenic design were removed and the lens scaled down for optimum characteristics at shorter object distances as they could be for Liquid Metal Ion (LMI) sources, very high beam current densities could be realized.

Our ion optical system is planned to be operated with an object distance of 8 mm which gives the beam characteristics listed in Table I. A magnified image of the source is produced at the blanking aperture. If this aperture is located at the center of the blanking

Ion Optical and Deflector System for HERMES II

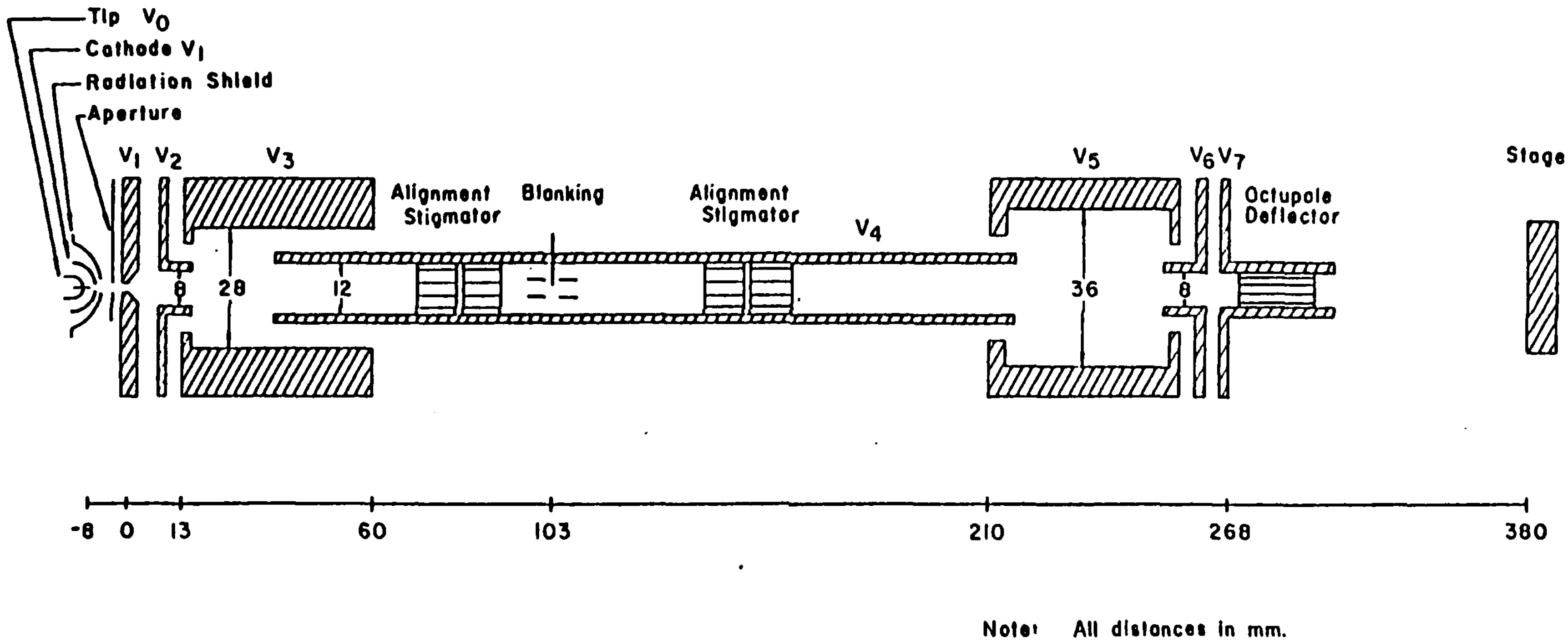


FIGURE 7

plates and the second lens (projector) focusses the blanking aperture on the substrate, the image of the beam will not move on the substrate as the beam is blanked but remain in a fixed position varying only in intensity. Sets of plates for alignment and stigmation of the beam are placed before the blanking plates and after them to provide the necessary critical control required in this ion optical system.

The second lens which is used to project the focussed probe onto the substrate has also undergone considerable CAD development. This lens must be an einzel lens (same potential in object and image space) so the blanking electrodes, the deflectors and the substrate can all be kept at ground potential. We have designed a lens with an asymmetrical electrode configuration: V_4, V_5, V_6, V_7. The total optical system will consist of two separate lenses but is shown in Fig. 7 with a long electrode, V_4, between them to emphasize that this region will be at ground potential to accommodate the blanking, alignment and stigmators near ground so their voltage supplies will not have to be floated to a high voltage.

The projector lens must also operate in the "zoom" mode if the beam energy is varied. Again this flexibility and the superior optical properties are obtained by using two central electrodes, V_5 and V_6, on which the voltages can be varied independently. The lens has been scaled up physically as much as reasonable to obtain the long focal length and low aberration coefficients needed to increase the working distance of the system. Larger aberration coefficients can be tolerated in the second lens because the system is operated with the first lens accelerating the beam and producing a magnified image; both factors reduce the angular divergence of the beam that the projector lens must accept. The probe sizes and deflection distances are set by the aberration figures of the focussed probe. The position, operating voltages and physical scale of the two lenses and position of the blanking aperture were adjusted with an optimization program to give the best compromise for obtaining the desired range of operation.

Figures 8-12 present the calculated data obtained for the system when operated at a final ion acceleration of 50 keV with varying angular apertures and deflection distances. Fig. 8 is a plot of the diameters of the axial spherical and chromatic aberration figures as a function of the acceptance half angle at the first lens. Since only the chromatic aberration figure changes with accelerating voltage, this image disk is also plotted for 30 keV. In presenting the data the diameter of the aberration disk is taken by adding the calculated aberration figures in quadrature. This procedure is rather arbitrary since the actual aberration figure will vary in character depending on which aberrations dominate in a particular case. All these data on the actual configuration of the aberration disks are, of course, available and will be used later to evaluate experimental data on resist exposures, modelling of the energy deposition in the resist by the ion beam and the effects of different development procedures in the pattern transfer processes.

TABLE I

Parameters and Characteristics of the Ion Beam Optical System when operated as indicated for the HERMES II. (Figure 7.)

First Lens:	$z = 0$ at 1st electrode, V_1.	
object focal length	$f_o = 9.94$ mm,	image $f_i = 22.23$ mm
Focal point F_o at	$z = -5.51$ mm,	F_i at $z = 14.18$ mm
Principal plane H_o at	$z = 4.43$ mm,	H_i at $z = -8.05$ mm
object at	$z = -8.0$ mm	image at $z = 103$ mm
	$M = 4.0X$, $C_s = 46$ mm, $C_c = 50$ mm	

Projector Lens:	$z = 0$ at 1st electrode, V_1.	
	$f_o = 59$ mm,	$f_i = 59$ mm
	F_o at $z = 188.4$ mm,	F_i at $z = 301.5$ mm
	H_o at $z = 247.2$ mm,	H_i at $z = 242.6$ mm

object for projector (beam blanking aperture) at $z = 103$ mm

image at (substrate) $z = 380$ mm

$M = 0.7X$, $C_s = 543.3$ cm, $C_c = 69.0$

Combined Lens:

object at	$z = -8.0$ mm,	image at $z = 380$ mm
	$M = 2.8X$, $C_s = 65$ mm, $C_c = 69.3$ mm	
	$MC_s = 182$ mm, $MC_c = 194$ mm	

Figure 9 has plots of the aberration figures as functions of aperture angle for several deflection distances. The curves show the disk diameters at the extremity of the given deflection. Clearly, if uniform lines are to be written in resists, the deflection distance with any given aperture must be limited to within a range in which the image figure does not vary markedly. This condition obtains for a 10 nm aberration figure produced by an α_0 = 2.45 mr deflected no more than ± 0.1 mm; for a 20 nm figure produced with an α_0 = 4.1 mr deflected over a distance of ≈ ± 0.2 mm; for a 100 nm (0.1μm) probe using an acceptance angle α = 8.0 mr deflected over ± 0.5 mm since at this apertue the aberration disk should be relatively insensitive to deflection distances because the aberration figure now is dominated by spherical aberration. Figure 10 contains plots of different aberration figures; spherical, coma, curvature of field, astigmatism, distortion, chromatic, deflection chromatic as functions of deflection, D, for several angular apertures, α.

The current density in the focussed probe, J_d, is of crucial interest in evaluating the potential of these ion beams for structuring and direct writing in resists. In Figures 11 and 12 the current densities for various deflection distances are shown as functions of α and the aberration disk respectively. The 2.45 mr acceptance angle producing a 10 nm probe is calculated to have the very high current density of ≈ 240 amp/cm^2 assuming the source to operate at an angular current density of $dI/d\Omega$ = 10μamp/cm^2. Using an α = 4.1 mr, a 20 nm probe would be obtained with a current density of 170 amp/cm^2, exposing four times the area with only a 29% drop in current density while permitting twice the deflection distances. For nanometer structure this would be a desirable operating condition unless lines less than 200 Å are needed.

If the system is to be operated to write larger minimum line widths rather than making multiple passes with a fixed line width, it would be an advantage to increase the angular aperture to obtain higher probe currents and obtain an image figure that is spherically aberration limited. The probe size then moves out of the region where the limiting aberration is transverse (deflection) chromatic aberration which limits the maximum deflection distance that can be used. At 50 kV a 6.25 mr acceptance half angle produces a 50 nm diameter probe that could be deflected ± 0.35 mm and have a current density of 65 amp/cm^2. To operate in the submicron range an 8 mr aperture could be used to produce a spherical aberration disk of 0.1μm with allowed deflections of ± 0.5 mm. The current density calculates to be 25 amp/cm^2.

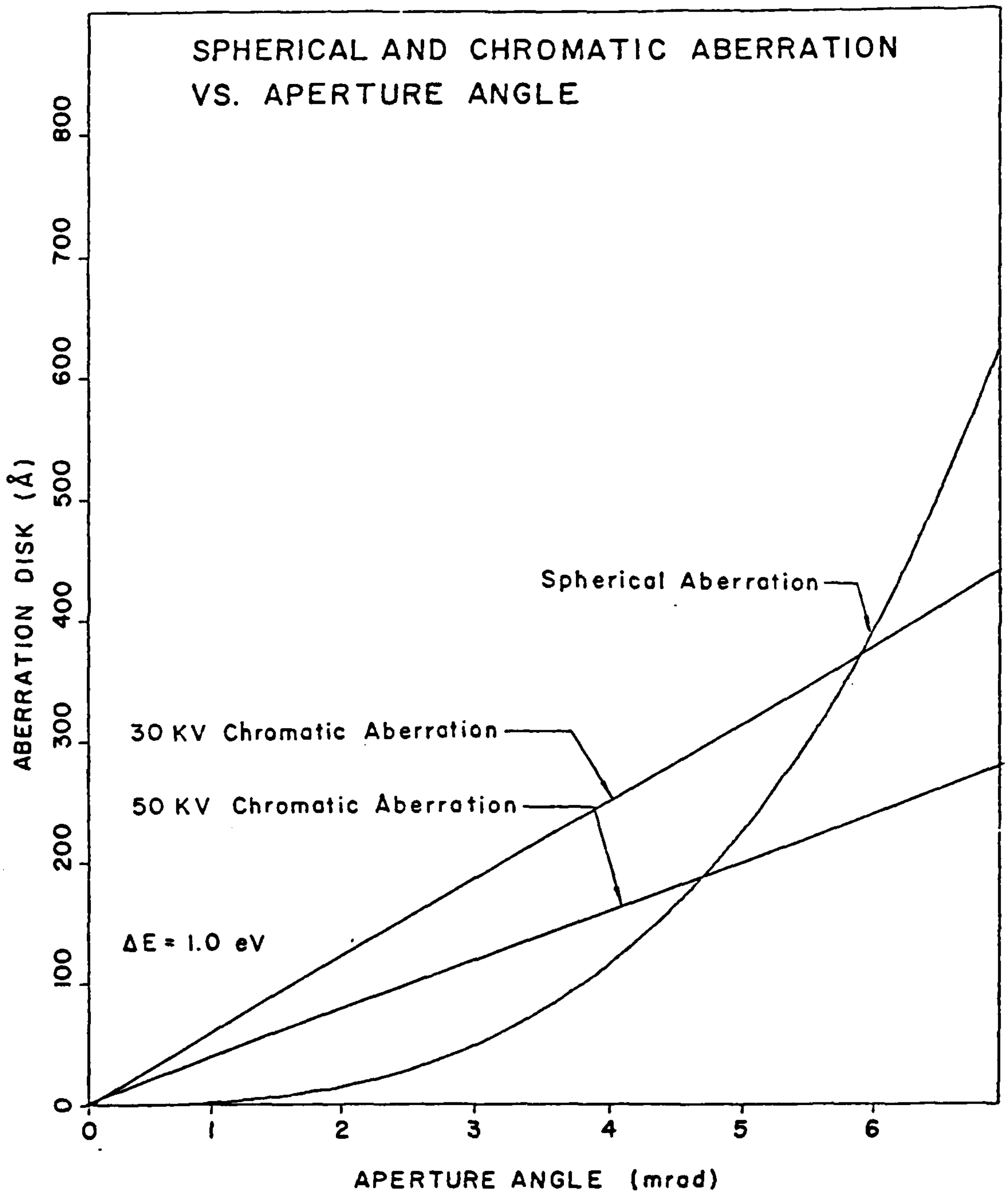

SPHERICAL AND CHROMATIC ABERRATION
VS. APERTURE ANGLE
ABERRATION DISK (Å)
800
700
600
500
400
300
200
100
0
Spherical Aberration
30 KV Chromatic Aberration
50 KV Chromatic Aberration
ΔE = 1.0 eV
0
1
2
3
4
5
6
APERTURE ANGLE (mrad)

FIGURE 8

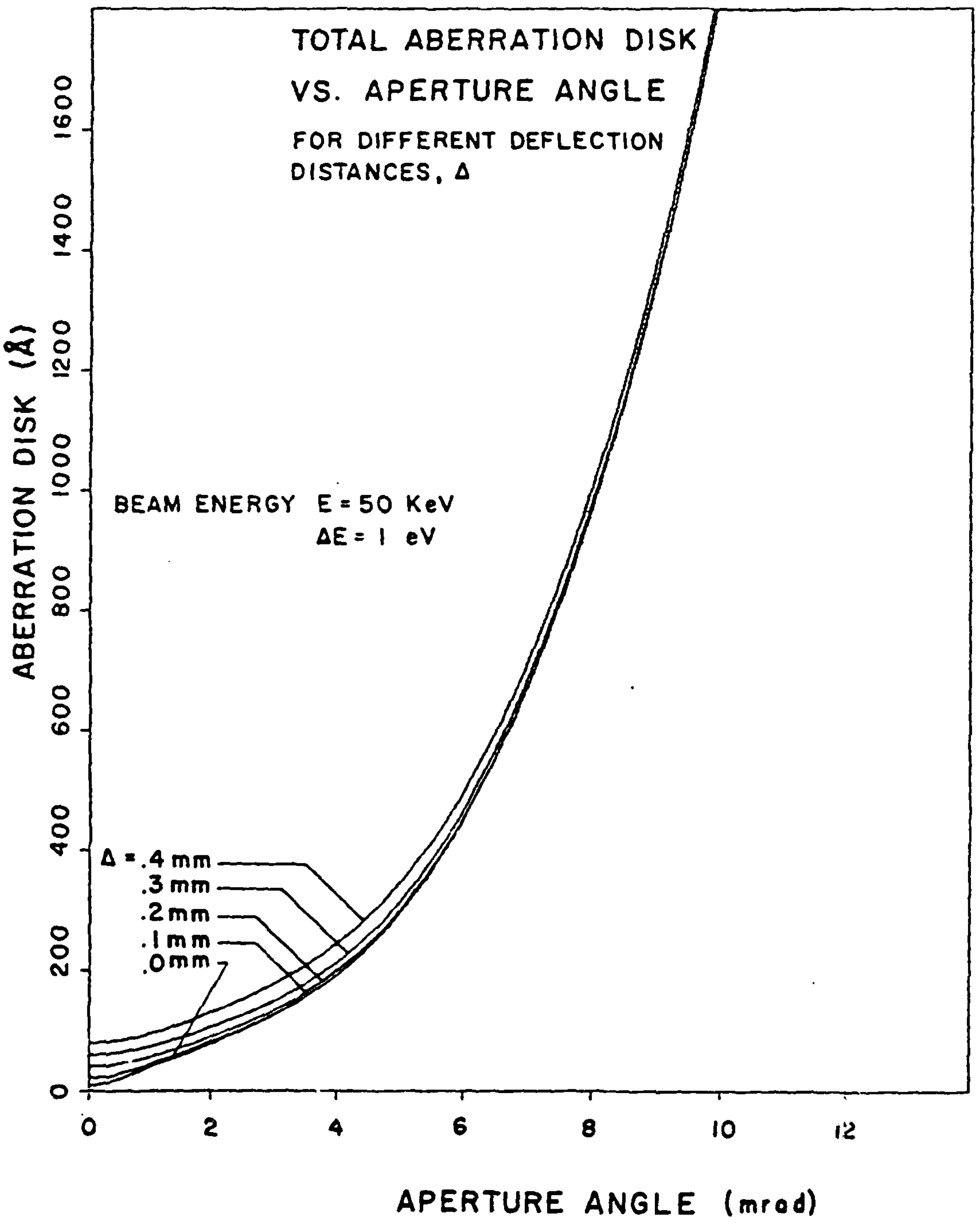

TOTAL ABERRATION DISK
VS. APERTURE ANGLE
FOR DIFFERENT DEFLECTION
DISTANCES, Δ
BEAM ENERGY E = 50 KeV
ΔE = 1 eV
Δ = .4 mm
.3 mm
.2 mm
.1 mm
.0 mm
ABERRATION DISK (Å)
0
200
400
600
800
1000
1200
1400
1600
0
2
4
6
8
10
12
APERTURE ANGLE (mrad)

FIGURE 9

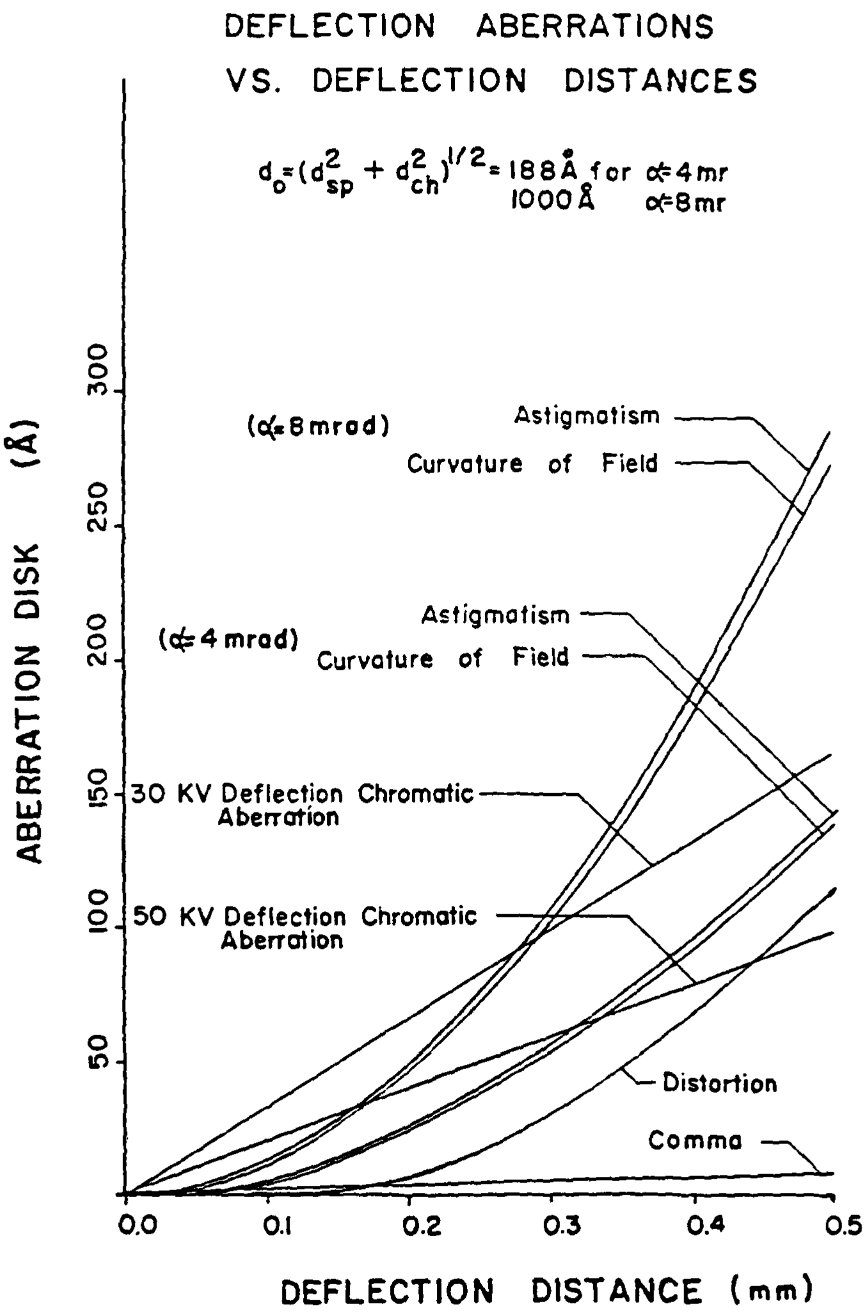

DEFLECTION ABERRATIONS
VS. DEFLECTION DISTANCES
$d_o = (d_{sp}^2 + d_{ch}^2)^{1/2} = 188\text{Å}$ for $\alpha = 4$ mr
1000Å $\alpha = 8$ mr
(α=8 mrad)
Astigmatism
Curvature of Field
(α=4 mrad)
Astigmatism
Curvature of Field
30 KV Deflection Chromatic Aberration
50 KV Deflection Chromatic Aberration
Distortion
Comma
ABERRATION DISK (Å)
50
100
150
200
250
300
0.0
0.1
0.2
0.3
0.4
0.5
DEFLECTION DISTANCE (mm)

FIGURE 10

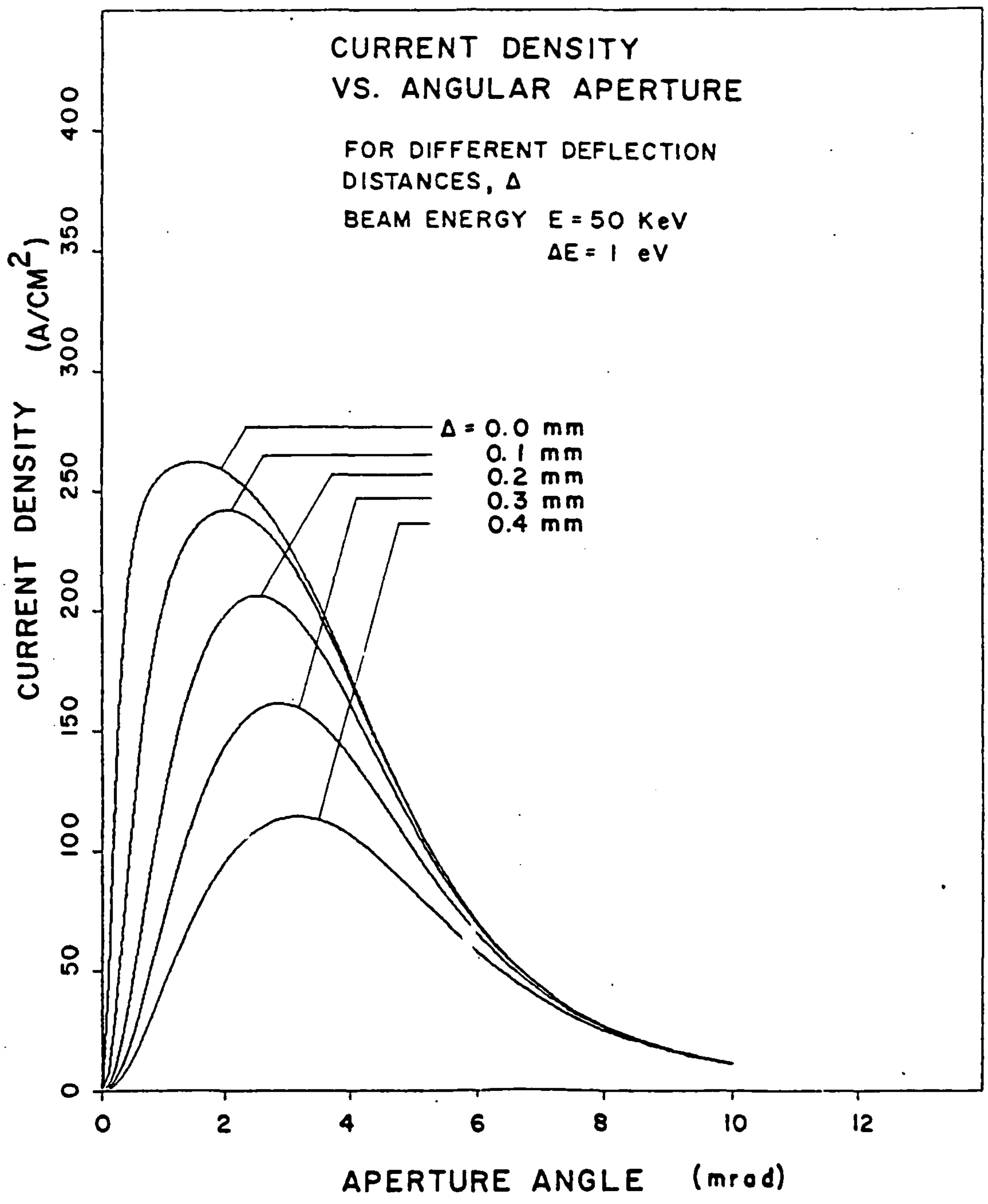
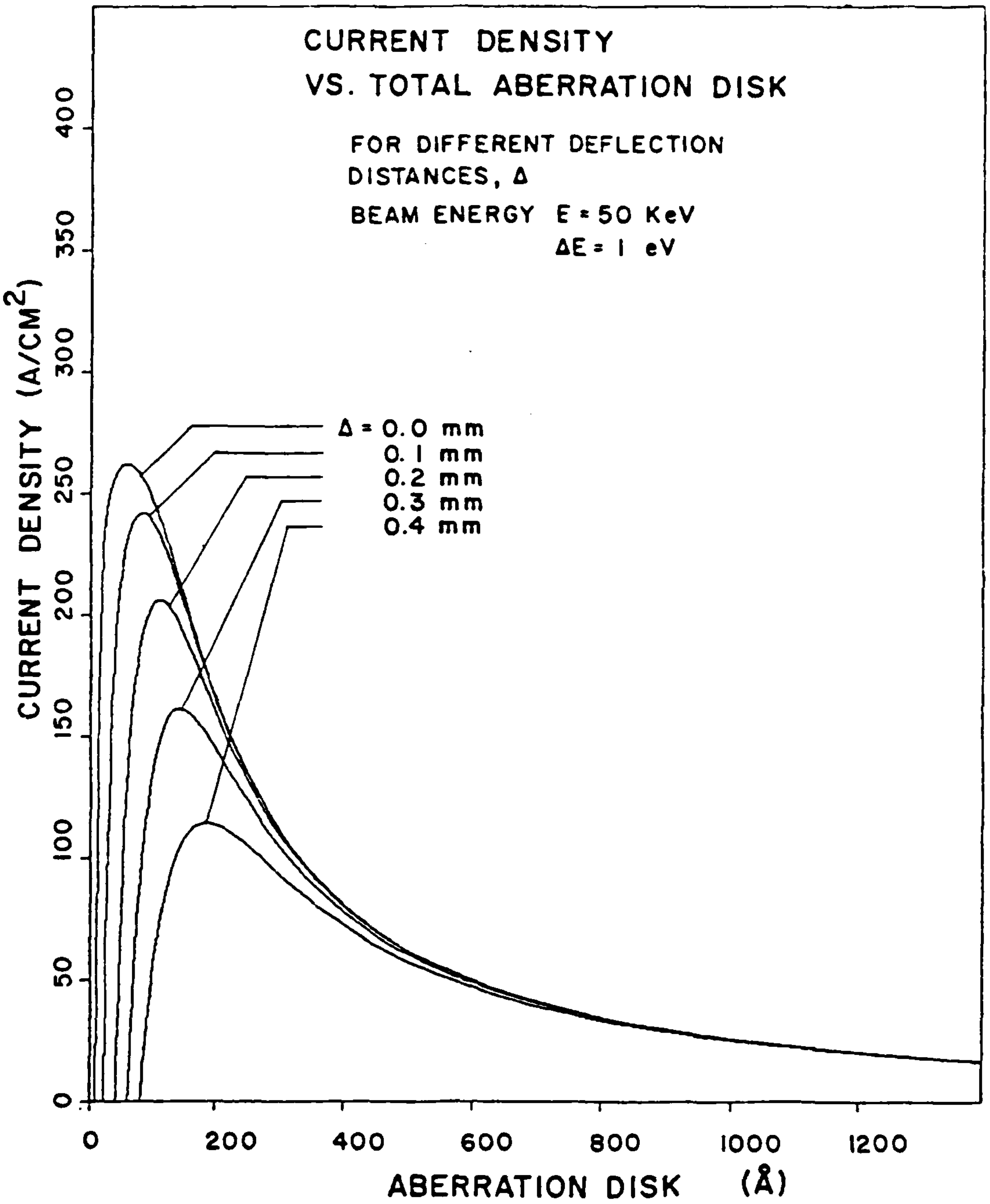

CURRENT DENSITY
VS. ANGULAR APERTURE
FOR DIFFERENT DEFLECTION
DISTANCES, Δ
BEAM ENERGY E = 50 KeV
ΔE = 1 eV
Δ = 0.0 mm
0.1 mm
0.2 mm
0.3 mm
0.4 mm
CURRENT DENSITY (A/CM²)
0
50
100
150
200
250
300
350
400
0
2
4
6
8
10
12
APERTURE ANGLE (mrad)

FIGURE 11



CURRENT DENSITY
VS. TOTAL ABERRATION DISK
FOR DIFFERENT DEFLECTION
DISTANCES, Δ
BEAM ENERGY E = 50 KeV
ΔE = 1 eV
Δ = 0.0 mm
0.1 mm
0.2 mm
0.3 mm
0.4 mm
CURRENT DENSITY (A/CM²)
0
50
100
150
200
250
300
350
400
0
200
400
600
800
1000
1200
ABERRATION DISK (Å)

FIGURE 12

These data are summarized in Table II for different beam energies from 30 keV to 60 keV. The higher resolution probes, 10 nm and 20 nm, have aberration figures that are dominated by chromatic and deflection chromatic aberrations and are proportional to $\Delta e/E$. Since the energy width is a constant $\Delta E = 1.0$ eV, the aberration figure is inversely proportional to the accelerating voltage V. The probes of 50 to 100 nm diameters are produced by increasing the aperture to the degree that the image figure is determined by spherical aberration which is proportional to the aperture angle, α^3, and gives a quite different aberration figure. These data are to be taken only as indications of the very high ion current densities that are to be expected in very high resolution ion probes using the ion source and optics we have developed. The actual energy distribution in a resist exposed to these probes will depend on the profile of the aberration figure in the focussed probe and other instrumental factors that will determine the final probe characteristics. While information can be obtained by computer modelling experiments, hard results will require a systematic study in the laboratory with the actual probe system.

TABLE II

HERMES II. Ion Optical System Characteristics For Various Probe Diameters and Beam Energies.

Probe diam. d_t and Deflection distance, D	Beam Energy E, ΔE=1.0 eV keV	Angular Aperture mrad.	Probe Current Density* amp/cm^2	Exposure Time ($S = 1\mu C/cm^2$) nanoseconds
d_t = 10 nm	60	2.8	310	3.2
	50	2.45	240	4.0
D = ± 0.1 mm	40	2.0	160	6.0
	30	1.7	100	10.0
d_t = 20 nm	60	4.25	180	5.5
	50	4.1	170	5.7
D = ± 0.2 mm	40	3.75	135	7.4
	30	3.0	90	12.0
d_t = 50 nm	60	6.4	67	14.9
	50	6.3	65	15.0
D = ± 0.35 mm	40	6.1	60	16.7
	30	5.75	53	19.0
d_t = 100 nm D = ± 0.5 mm	60 to 30	8.0	25	40.0
		Spherical aberration limited therefore independent of voltage.		

*Angular current density of source $dI/d\Omega = 10\mu a/sr$.

CONCLUSIONS

We have reached the stage in our instrumental development of the FIPS I at which we should be obtaining data on the H_2^+ ion-resist interactions and can begin systematic investigations on resist exposures and resolution. We have access to a wide range of processing and pattern transfer techniques as members of the NRRFSS. These extensive facilities and the research that is being carried out on new methods for submicron processing will enable us to test a number of procedures and methods in our exploration of this very high resolution lithography. There is every indication that we will have to investigate new resists and methods to obtain patterning in the 10-20 nm range of dimensions. Exposing a 10 nm pixel in a resist like PMMA which has a sensitivity to ions of 0.5 to 1μC/cm^2 would mean that only 3 to 5 H_2^+ ions would be needed to expose each pixel area. Clearly the shot noise would be very bad and it will be necessary to go to much less sensitive resists for this very high resolution structuring. Developing new less sensitive resists for high resolution lithography can be an advantage in the fact that the resists can now be chosen not on the basis of their sensitivity but on on the basis of their physical properties and the characteristics required in the subsequent processing steps in the fabrication of devices.

The electron beam system, "HERMES," that we have been given by Hewlett-Packard presents a challenge and a unique opportunity to develop a real ion beam lithography capability for fabricating devices on a laboratory scale. Converting the electron beam column to a very high quality ion beam column is a large but relatively straightforward task that I believe we can accomplish successfully. We have all the basic designs in hand and they can now be executed. The extensive electronic subsystems controlled under the H-P 1000F computer represent very advanced state of the art, high speed electronics designed to obtain the high throughput capability required in a production environment. We are in the stage of evaluating which of the subsystems can be used and maintained as is and what parts of the total system we will have to modify or replace with electronic systems that are adequate for advanced lithography in a laboratory environment. We will have to have systems that are within our resources to construct and maintain and it may well be that subcontracting for the construction of one or two of the subsystems may be the best way to proceed. In any case, we plan to have an Ion Beam Lithography system capable of fabricating real devices and new structures in the submicron and nanometer range.

We will have the very strong auxiliary support at Cornell through the National Research and Resource Facility for Submicron Structures (NRRFSS) and the the collaboration of the many faculty, students and support staff who are working at the forefront of high resolution structuring and development of new devices. We are in a unique position to exploit our IBL capability in new and significant directions.

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H. Ohiwa, R.J. Blackwell and B.M. Siegel, "Design of an electrostatic ion optical system for microfabrication with 100 Å resolution," J. Vac. Sci. Technol. 19, 1074 (1981).

B.M. Siegel, G.R. Hanson, M. Szilagyi, D.R. Thomas, R.J. Blackwell, H. Paik, "Ion beam lithography system using a high brightness H_2^+ ion source," Proc. SPIE 333, 152 (1982).

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PERSONNEL

Name	Position	% of Full Time	
Benjamin M. Siegel	Principal Investigator	50%	
Miklos Szilagyi	Senior Research Assoc.	100%	2/81 - 7/82
Earl J. Kirkland	Postdoctoral Assoc.	33%	10/82 -
H. Ohiwa	Visiting Assoc. Professor	100%	6/80 - 8/80
George N. Lewis	Postdoctoral Assoc.	100%	9/82 -
David R. Thomas	Research Specialist	100%	6/80 - 9/82
John Mioduszewski	Research Specialist	100%	10/82 -
David H. Weiner	Electronics Res. Spec.	100%	9/82 -
Richard J. Blackwell	Grad. Research Assistant	50%	6/80 -
Joel A. Kubby	Grad. Research Assistant	50%	6/82 -
Hongyul Paik	Grad. Research Assistant	50%	9/81 -
Alan J. Schwartz	Laboratory Assistant (4th year Eng. Student)	10 hrs/wk	6/82 -